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Simulation of air quality and operational cost to ventilate swine farrowing facilities in Midwest U.S. during winter

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Abstract

We have developed a time-dependent simulation model to estimate in-room concentrations of multiple contaminants [ammonia (NH_3), carbon dioxide (CO_2), carbon monoxide (CO) and dust] as a function of increased ventilation with filtered recirculation for swine farrowing facilities. Energy and mass balance equations were used to simulate the indoor air quality (IAQ) and operational cost for a variety of ventilation conditions over a 3-month winter period for a facility located in the Midwest U.S., using simplified and real-time production parameters, comparing results to field data. A revised model was improved by minimizing the sum of squared errors (SSE) between modeled and measured NH_3 and CO_2. After optimizing NH_3 and CO_2, other IAQ results from the simulation were compared to field measurements using linear regression. For NH_3, the coefficient of determination (R^2) for simulation results and field measurements improved from 0.02 with the original model to 0.37 with the new model. For CO_2, the R^2 for simulation results and field measurements was 0.49 with the new model. When the makeup air was matched to hallway air CO_2 concentrations (1,500 ppm), simulation results showed the smallest SSE. With the new model, the R^2 for other contaminants were 0.34 for inhalable dust, 0.36 for respirable dust, and 0.26 for CO. Operation of the air cleaner decreased inhalable dust by 35% and respirable dust concentrations by 33%, while having no effect on NH_3, CO_2, in agreement with field data, and increasing operational cost by $860 (58%) for the three-month period.

Keywords

Livestock; Simulink; Inhalable dust; Respirable dust; Ammonia; Carbon dioxide

1. Introduction

Modern swine barns are generally enclosed structures producing a high density of swine. Feed, swine, and swine manure contribute to elevated concentrations of hazardous airborne dust and gases in these structures. Swine barn dust suspended in the air is composed of feed, feces, mold, pollen grains, insect parts, and mineral ash (Donham et al., 1986). Various gases, including ammonia (NH_3), methane (CH_4), and hydrogen sulfide (H_2S), are released

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from the digestion of swine manure stored in the pit below the floor. Carbon dioxide (CO_2) is generated by the respiration of swine (Donham, 1988; Chang et al., 2001) and can be generated from in-room heaters. Inhalation of these dusts and gases have been associated with adverse health outcomes in swine workers (Donham et al., 1986; Donhamet al., 1989; Larsson et al., 1994; Donham et al., 1995; Iversen et al., 2000; Kirkhorn and Garry, 2000; Donham et al., 2002; Charavaryamath et al., 2005; Hong et al., 2012) and may also depress the health status of swine (Stombaugh et al., 1969; Drummond et al., 1980; Donham, 1991; Diekman et al., 1993; Pedersen et al., 2000). Recommendation maximum concentration of total dust is 2.4 mg m^{-3} for workers (Donham et al., 1989) and 3.7 mg m^{-3} for swine (Donham, 1991). For both workers and swine, the recommended maximum concentrations of respirable dust particles and CO_2 are 0.23 mg m^{-3} and 1,540 ppm, respectively (Donham et al., 1989). The recommended maximum concentration of NH_3 is 7 ppm for workers (Donham et al., 1989) and 11 ppm for swine (Donham et al., 1991).

Mechanical ventilation through pit fans and radial fans at one end of the room is commonly used to maintain temperatures slightly above ambient temperature during the summer and maintain low gas and dust levels by removing these impurities from the room during the winter. Room or pit air is mechanically exhausted, which pulls clean outside air to flow into the barn. In upper Midwest facilities during winter, however, room exhaust fans are typically unused since replacement air must be heated, resulting in increased heating cost (Peters et al., 2012). Lower ventilation rates lead to higher dust concentrations in winter compared to summer (O'Shaughnessy et al., 2010; Takai et al., 1998). Most producers run pit fans in the winter to exhaust air above the under-floor manure pits, and Reeve et al. (2013) found that the use of pit fans in winter reduced dust, NH_3 and H_2S concentrations in a farrowing facility, but not necessarily below concentrations recommended to protect worker health.

Numerous researchers have used computer simulations or modeling to study the effect of mechanical ventilation in livestock facilities on indoor air quality (IAQ) and energy consumption (Pedersen et al., 1998; Soldatos et al. 2005; Cortus et al., 2010b). Anthony et al. (2014) evaluated the effectiveness of treating and recirculating air using multiple flow rates, percent dilution with outside air, and contaminant control devices for a representative swine farrowing room using a simulation model developed by Park et al. (2013). In Anthony et al. (2014), indoor dust concentrations were reduced (41% for respirable and 33% for inhalable) with the system in operation, while gas concentrations (NH_3, CO, and CO_2) were unchanged. Their study provides an evidence that incorporating standard ventilation controls can serve to reduce dust concentrations without increasing concentrations of gaseous contaminants. In Park et al. (2013), a mass and energy balance model was developed and evaluated to examine the relationship between IAQ, wintertime ventilation, air pollution control equipment, and heating needs. Outdoor temperatures were simulated based on seasonal estimates, and production levels (sow and piglet counts) and manure pit volume were held constant. However, NH_3 concentrations estimated by the model were substantially lower than those observed in swine farrowing rooms. Simplifications used in the original model included the use of a fixed NH_3 generation rate based on emission data measured in an Iowa farrowing barn (Cortus et al., 2010a), which did not consider swine number and manure volume in the pit. Cortus et al. (2009) developed a more complex equation to estimate NH_3 generation rate using temperature, total ammonia nitrogen (TAN)

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concentration and pH to calculate the NH_3 generation rate from the slurry surface. However, real-time measuring these variables is difficult. The simulation model of Park et al. (2013) may be improved by empirically incorporating room NH_3 measurements into the model.

Room concentrations of CO_2 estimated by the simulation model of Park et al. (2013) were also lower than those observed in swine farrowing room (Reeve et al., 2013). In Park et al. (2013), the CO_2 concentration for makeup (outdoor) air into the room used as input value of 400 ppm, typical of ambient concentrations. However, CO_2 concentration in rooms adjoining the simulated farrowing room, particularly the adjoining hallway that separates the study room and two other production areas (farrowing, nursery) may contribute substantially to makeup air into the test room. Therefore, an examination of appropriate makeup CO_2 concentration is required to improve the input value in the simulation model.

Room concentration measurements from field testing of a farrowing barn while deploying the optimized ventilation system are available to allow validation of the simulation model (Anthony et al., 2014). Outdoor temperatures, pit wall temperatures, and barn occupancy data were collected with room contaminant concentration data, providing data to validate the simulation model estimates. Understanding whether the time-dependent production factors or simplified seasonal temperature and production capacity numbers are sufficient to generate realistic concentration estimates in the barn over a winter can be examined using this robust data set.

The overall objective of this study was to improve the mass balance model to simulate the IAQ. The specific objectives were to: (1) enhance the preexisting model using an empirical model to simulate the NH_3 emission from slurry, (2) determine the extent to which realistic outdoor temperature and animal population within the barn are necessary to accurately estimate room concentrations (NH_3, CO_2, CO, and dust), and (3) validate the improved model using the field measurements.

2. Materials and Methods

2.1. Simulated swine farrowing facility

A generalizable model was developed, but parameters were assigned to represent the building and operation of a specific swine farrowing facility (Mansfield Swine Education Center at Kirkwood Community College, Cedar Rapids, Iowa, U.S.). Previous studies (Reeve et al., 2013; Park et al., 2013) fully described this facility (e.g., dimensions and airflow rates) with key parameters provided briefly here. Four radial wall fans positioned on the north and south room walls were not in operation during the winter. Two pit fans removed air above the manure pits, exhausting air out the west side of the building (Q_{tp}, 0.82 $m^3\ s^{-1}$) (Fig. 1(a)). During field testing described by Anthony et al. (2015), a single, gas-fired heater maintained room temperatures by cycling on when room temperature dropped below 20.0°C and off when temperature exceeded 22.2°C. Electrical heating lamps were positioned in crates when piglets were present. A combination of metal and plastic slats separated the swine crates from the manure pits below. Two pit fans exhausted air to outside of the building at an airflow Q_{ae} through the slatted floor and over the manure pit located under the four rows of crates (19 total crates). An air cleaner (shaker dust collector; Model

140, United Air Specialists Inc., USA) was installed outside the building. The air cleaner exhausted barn air at the flowrate of 0.47 $m^3\ s^{-1}$ (1000 $ft^3\ min^{-1}$) with an internal fan, filtered the dust, and returned 100% of the treated air to the building. The air cleaner was operated with a standard fabric filter (14-pocket polyester sateen filter, United Air Specialists Inc., USA) used in Peters et al. (2015).

The simulated room volume was divided into two sections (a habitable portion and the manure pit), as shown in Figure 1(b) with key parameters described in Table 1. The habitable section was modeled as a rectangular box, dimensioned to match the test facility, as shown in Figure 1(a). The manure pit headspace was modeled as four equally-sized rectangular boxes. In the original model, total pit headspace volume was fixed at 67.5 m^3 (Park et al., 2013; Anthony et al., 2014). In the new model, total pit headspace volume decreased over time as the pit was filled with swine manure over the three-month period. The pit head space volume, V_p, was calculated as follow:

$$V_p(t)=V_{p,max}-\dot{G}_{slurry}\times m_{swine}\times t,\ \ (V_{p,min}\le V_p\le V_{p,max}) \quad (1)$$

where $V_{p,max}$ (= 67.5 m^3) and $V_{p,min}$ (= 20.8 m^3) are the maximum and minimum volumes of pit head space, respectively. Initial V_p was set to $V_{p,max}$ representing an empty pit. $\dot{G}_{slurry}$ is the slurry generation rate per unit swine mass and m_{swine} is the total mass of sows and piglets at a given time. In the original model, the swine number was fixed and was not coupled with pit head space volume (Park et al., 2013; Anthony et al., 2014). The new model used real swine occupancy of the field test site, provided in detail in supplemental materials as Table A2.

In the original model, outdoor temperature (T_o) was simulated using historical seasonal average data for the Cedar Rapids, Iowa, modeled as a combination of two sine waves (Park et al., 2013; Anthony et al., 2014) to account for within and between day temperatures. In contrast, in the current model, T_o was set to the actual temperature of Cedar Rapids, Iowa, U.S. from December 2013 to February 2014, the period of the field study for model validation (CID Airport meteorological data from NOAA's National Climatic Data Center), where at least hourly temperatures were available. Model equations for temperature and operational cost are documented in supplementary, with electrical (0.0807 $ kWh^{-1}) and natural gas (0.27 $ m^{-3}) based on industrial pricing in Iowa (December 2013 to February 2014).

The simulation starting time was 8:00 a.m. on December 1st and proceeded through the end of February (90 days). This project generated a time-dependent simulation model using MatLab® R2014a (version 8.3.0.532, MathWorks, Inc., U.S.) with Simulink® (version 8.3, MathWorks, Inc., U.S.).

2.2. Model equations and parameters for IAQ

Gas and dust concentrations in the room were simulated simultaneously with energy balance equations (equations A1 and A2, in supplemental materials). Under the assumption of a well-mixed indoor space, the mass-balance equations for NH_3, CO_2, CO and dust for the room and pit volumes were as follows (Park et al., 2013):

Room:

$$V_r \frac{dP_r}{dt} = Q_{ac}\left(1-\eta_P\right)P_r + Q_{tp}P_o + Q_{ae}P_p + \dot{G}_{Pr} - Q_{ac}P_r - Q_{tp}P_r - Q_{ae}P_r \quad (2)$$

Pit:

$$V_p \frac{dP_p}{dt} = Q_{tp}P_r + Q_{ae}P_r + \dot{G}_{Pp} - Q_{tp}P_p - Q_{ae}P_p \quad (3)$$

where P_o is the outdoor concentration, P_r is the room concentration, and P_p is the pit concentration. Values for the input parameters for the contaminant generation rate for the room ($\dot{G}_{Pr}$) and for the manure pit ($\dot{G}_{Pp}$) and the removal efficiency of the air cleaner (η_P) are given in Table 2. In the original model, the NH_3 generation rate was independent of swine number and manure volume in the pit: NH_3 had been fixed at 1.11 mg s^{-1} (Park et al., 2013). In the current model, NH_3 generation rate was replaced with a dynamic value. To calculate the CO_2 concentration, simulation values for the makeup air CO_2 concentration were optimized and constrained between 400 ppm (ambient air quality outside) and 1,750 ppm (concentrations in the adjoining hallway).

2.2.1. Generation rate of NH_3—Generating NH_3 is a process of mass transfer from the NH_3 solution to the free atmosphere. The generation rate of NH_3 can be calculated as follows (Aarnink and Elzing, 1998):

$$\dot{G}_{NH3} = \frac{k \times A_p \times f \times TAN}{H} \quad (4)$$

where k is the mass transfer coefficient, A_p is the surface area of the manure, f is the un-ionized fraction of the total ammoniacal nitrogen (TAN) and H is the Henry constant. The mass transfer coefficient can be described by the following equation (Aarnink and Elzing, 1998; Bjerg et al., 2013):

$$k = Z \times v_s^{0.8} \times T_{film}^{-1.4} \quad (5)$$

where Z is the empirically determined constant, v_s is the air speed in the vicinity of the slurry, and T_{film} is the surface temperature of the slurry. Measuring or estimating values for f, TAN, and H are difficult because they change over time. Therefore, a new empirical model was proposed to estimate the generation rate of NH_3 in the pit ($\dot{G}_{NH3p}$,) based on m_{swine} and T_{film}. The $\dot{G}_{NH3p}$ was calculated as follow equations:

$$\dot{G}_{NH3p} = Z_{NH3} \times \frac{m_{swine}}{500kg} \times \dot{G}_{NH3,EM} \times T_{film}^{-1.4} \quad (6)$$

where Z_{NH3} (units: $K^{1.4}$ $m^{0.2}$ $s^{-0.2}$) is the coefficient determined by fitting modeled concentration estimates to field measurements. The Z_{NH3} includes ventilation air speed (v_s) and slurry conditions (f, TAN and pH). $\dot{G}_{NH3,EM}$ is the NH_3 emission rate per 500 kg swine, and a standard 1.5 mg s^{-1} per 500 kg swine was used (Heber et al., 2000).

2.2.2. Generation rate of CO_2 and makeup air CO_2 concentration—Sources of CO_2 inside the room included gas-fired heater exhaust, swine exhalation, and digestion of slurry in the pit. CO_2 generation rate by heaters was assumed to be zero when off and 906 mg s^{-1} when on, which was calculated as (Park et al., 2013):

$$\dot{G}_{CO2r,heater} = \dot{Q}_{heater} \times ER_{CO2} \quad (7)$$

where $\dot{Q}_{heater}$ is the natural gas consumption of the gas heater in use at the test site (= 0.000472 m^3 s^{-1}) and ER_{CO2} is the CO_2 emission rate from natural gas combustion (= 1,920,000 mg m^{-3}) (EPA, 1998). The generation rate of CO_2 by swine respiration was equal to 0.000201 m^3 h^{-1} W^{-1} (Blanes and Pedersen, 2005). Total generation rate of CO_2 by swine respiration was calculated as:

$$\dot{G}_{CO\ 2r,swine} = \frac{0.000201 \times \rho_{CO\ 2} \times 1000000}{3600} \times \dot{q}_{swine}. \quad (8)$$

where ρ_{CO2} is the density of CO_2 (1.84 kg m^{-3}) and $\dot{q}_{swine}$ is the total heat generation rate from swine (Table A1). For converting unit, 1,000,000 mg kg^{-1} and 3,600 s h^{-1} were used. The generation rate of CO_2 from slurry in the pit was assumed as 37.5% of swine exhalation (Ni et al., 1999). The north, south, and west wall of simulated room face to outdoor area. However there is a hallway outside east wall. The hallway CO_2 concentration was observed larger than 1,500 ppm. Makeup air pulled by pit fans may include the air from the adjoining hallway. Therefore, the model was run with CO_2 concentrations assumed as makeup air: 400 ppm as used in the original model (Park et al., 2013); 750 ppm to reflect published in-room concentrations by Chang et al. (2001); 1,250, 1,500, and 1,750 ppm to reflect field concentrations measured in the adjacent hallway that served as a source of some of the makeup air exhausted by fans in the field test site. The impact of these different CO_2 input concentrations were assessed.

2.2.3. Generation rates of CO and dust—Generation rates of CO and dust used in the current model were the same as in the original model (Park et al., 2013). However, inputs for the swine number and outdoor temperature were changed to match field conditions over the 2013–14 field study period. CO was generated by gas-fired heaters in the room since combustion gases were not vented out of the room; simulation of the heater operation (on vs off) was triggered by the need to maintain production temperatures in the room (20.0–22.2°C) as a function of heat loss from outside temperature changes. When the heaters were turned on, the CO generation rate was 0.6 mg s^{-1}, which was calculated using:

$$\dot{G}_{COr}=\dot{Q}_{heater} \times ER_{CO} \quad (9)$$

The CO emission rate from natural gas combustion, ER_{CO}, used 640 mg m^{-3} (EPA, 1998).

The dust generation rate in the room, $\dot{G}_{dustr}$, was modeled for both inhalable dust (1–100 µm in diameter) and respirable dust (1 to 10 µm in diameter, with 50% cut point of 4 µm), as defined by the ACGIH (2016). Generation rates were calculated as follow:

$$\dot{G}_{duster}=\dot{G}_{mean} \times \frac{m_{swine}}{500kg}. \quad (10)$$

where $\dot{G}_{mean}$ is the overall mean dust generation rate per 500 kg swine and m_{swine} is the total mass of swine in kg. The $\dot{G}_{mean}$ for inhalable and respirable dust were 0.1575 and 0.0164 mg s^{-1}, respectively (Takai et al., 1998). To account for the fact that dust generation depends on feeding time, dust generation rate was assumed to increase during feeding as shown in Figure A1. The first and second feedings were modeled to occur at 9:00 a.m. for 30 min and 4:00 p.m. for 30 min, respectively. Dust concentrations at the first and second feeding were modeled as four and two times higher than the mean daily concentration, respectively, based on previous field studies (O'Shaughnessy et al., 2010).

2.3. Field measurements

In our previous study (Anthony et al., 2015), experimental data were collected in the swine farrowing facility. Field sampling was conducted on 18 days from 13 December 2013 to 27 February 2014. The air cleaner was off for seven (13 to 19 December; 22 to 27 January; 26 to 27 February) and on (20 December to 21 January; 28 January to 25 February) for 11 of the sample days. Twenty-four hour (from 8:00 a.m. to 8 a.m.) monitoring was conducted throughout the study period at six fixed positions, indicated as A through F (height of 1.5 m) in Figure 1(a). All devices were pre- and post-calibrated in the laboratory for each sampling event. IAQ concentration data included NH_3, CO, CO_2, and dust (inhalable and respirable). NH_3 and CO were measured by VRae (Rae Systems, USA). CO_2 was measured by ToxiRae (Rae Systems, USA). Inhalable dust was sampled by IOM sampler (225-70A, SKC, USA) at 2 L min^{-1} with 25 mm polyvinyl chloride (PVC) filters (5 µm pore, 25 mm, SKC, USA), and respirable dust was sampled using a cyclone (GK2.69, BGI, USA) with PVC filters (5 µm pore, 37 mm, SKC, USA) at a sampling flow rate of 4.2 L min^{-1}. A micro-balance (MT5, Mettler-Toledo, USA) was used to pre- and post-weigh the PVC filters to obtain room dust concentrations. Data averaged over all six positions and 24 hours were used to validate simulation model.

2.4. Simulation scenarios and data analysis

Park et al. (2013) previously reported the sensitivity between inputs and outputs using a simulation model for various conditions of outdoor temperature, wall insulation, pit-air-exchange ratio, pit fans, recirculation ratio, and filtration efficiency. Pit-air-exchange ratio (r_{ae}), T_o, wall insulation (U_{rw}), and recirculation ratio (r_r) affected heater operational cost. Outdoor temperature (T_o) and r_r were more sensitive to heater operation than U_{rw} and r_{ae}. The pit-air-exchange ratio (r_{ae}) and r_r affected room NH_3, CO and CO_2 concentrations, although NH_3 was the most sensitive to the r_{ae} because the only NH_3 source was in the pit. However, CO and CO_2 concentration were more sensitive to the r_r than the r_{ae} since significant CO and CO_2 sources were in the room and not only the manure pit. Additional tests for sensitivity were not conducted because they are unchanged with the same mass balance equation used in both models. Constant values for r_{ae} (0.1) and r_r (1) were used, based on this previous analysis.

Simulations were performed for the ventilation with pit fans and recirculation with a dust filtration system. Simulation parameters are given in Tables 1 and 2. The operation condition of air cleaner in the model was represented one in field test (in Table A3). Results from simulations were compared to field measurements. Linear regression was used to identify slope and intercept between calculated and field measured data. The coefficients of determination (R^2) were calculated using Excel 2010 (Microsoft, USA).

Simulations were performed to optimize NH_3 and CO_2 modeling first. To improve the NH_3 model with empirical generation rate, simulations were performed preferentially with five values (15,000, 20,000, 21,000, 21,500 and 25,000) for Z_{NH3}. Additional simulations were performed with three replacement air CO_2 values (400, 750, 1250, 1500 and 1750 ppm) to find an appropriate value for CO_2 concentration in makeup air. The simulation with the minimum sum of squared error (SSE) was used to identify the optimum NH_3 generation rate factor and makeup air CO_2 concentration. The SSE was calculated using NH_3 and CO_2 concentrations from simulation (P_s) and measurement (P_m) as follows:

$$SEE = \sum (P_m - P_s)^2 \quad (11)$$

The values for Z_{NH3} and makeup CO_2 concentration which showed small SSE were chosen for further simulations.

Once the model was optimized to minimize the SSE for NH_3 and CO_2, three time-dependent conditions were also assumed for the operation of the air cleaner. First, the air cleaner was modeled in the “off” condition for the entire winter, then the system was simulated with the ventilation system “on”. Finally, the air cleaner was represented on-off operation cycle in field test for the entire winter. This allowed an assessment of operating cost and air quality differences between using the air cleaner or not. For these simulations, real swine occupancy and real outdoor temperature were used. All other parameters were fixed as shown in Tables 1 and A1.

3. Results and discussion

3.1. Improving simulation models for NH_3 and CO_2

3.1.1. Optimization for NH_3 with Z_{NH3}—Room NH_3 concentrations from the original model (Park et al., 2013), the new model and field measurement are shown in Figure 2(a). In the original model of Park et al. (2013), the NH_3 concentration was 0.17 ppm and did not change because r_{ae} (= 0.1), pit fan operation, and r_r (= 1) of the air cleaner were fixed. The resulting R^2 was 0.02, indicating that estimates of NH_3 made with the original model reflected reality poorly. The linear regression between measured and new model simulated NH_3 concentration had a modest R^2 (= 0.37), which is, however, substantially improved over the original model (Table 3). The difference of Z_{NH3} did not change R^2. The improvement is attributed to difference of Z_{NH3} affected NH_3 concentration only. When the Z_{NH3} was 15,000, NH_3 concentrations from the new model ranged from 0.03 to 10.59 ppm. When the Z_{NH3} increased to 25,000, NH_3 concentrations ranged from 0.06 to 17.65 ppm. When the Z_{NH3} was 21,000, SSE was 438, which was smaller than 601 at Z_{NH3} = 15,000 or 524 at Z_{NH3} = 25,000. The value of Z_{NH3} was fixed to 21,000 for further simulations.

With the Z_{NH3} fixed at 21,000, the 24-hour averaged NH_3 concentration from the simulations ranged from 0.05 to 15 ppm, while field NH_3 concentrations ranged from 0.07 to 28 ppm (Table A4). Anthony et al. (2015) reported that both the number of sows and T_o were significant factors to estimate 24-hour NH_3 concentrations. When the swine number was zero at −13.4°C (December 31), the simulated and measured NH_3 concentration were 0.05 ppm and 0.07 ppm, respectively. However, when the sow number was 17 at −13.0°C (26 February), the simulated and measured NH_3 concentration increased to 13.44 ppm and 7.25 ppm, respectively. Outdoor temperature could affect T_g since the pit wall is an exposed structure above the ground. However, T_g used in Eq. 6 was assumed to be a fixed value. Outdoor temperature might be considered in Z_{NH3} instead of T_g. If measuring and simulating time-dependent T_g are available, simulation can be improved.

3.1.2. Optimization for CO_2 with makeup air CO_2 concentration—Estimates of CO_2 concentrations from simulations for each formulation of makeup CO_2 concentrations are compared to field measurement in Figure 2(b). Room CO_2 concentrations were underestimated when the makeup air CO_2 was assumed to be 400 and 750 ppm. When 1,500 ppm was used as the assumed makeup air CO_2, the trend line (dot line) crossed 1:1 line (grey line). The CO_2 concentration in the hallway adjacent to the farrowing room in the field studies ranged from 1,010 to 3,330 ppm (mean 2,140 ppm), indicating that if makeup air into the farrowing room came from the hallway. It would be closer to 1,500 ppm that was simulated. When the makeup air CO_2 concentration was 1,500 ppm, SSE was 1.1×10^6. When the outdoor concentration simulations used 1,750 or 450 ppm, SSE was increased 2.5 and 18 times, respectively. The makeup air CO_2 concentration was set to 1,500 ppm for further simulations.

Estimates of farrowing room CO_2 concentrations ranged from 2,103 to 2,755 ppm (using makeup air CO_2 = 1,500 ppm, Table A4). Room CO_2 concentrations exceeded comfort levels established by ASHRAE 62-1999 (1000 ppm) and were generally higher than industry recommendations (1,540 ppm) (Donham et al., 1989). Anthony et al. (2015) reported that piglet number and T_o are significant factor for estimations of room CO_2 concentration. Similar to their results, simulated CO_2 concentrations increased when the T_o decreased or swine number increased. Room CO_2 concentration was highest during the coldest day because the heater, which produces CO_2, must operate more frequently and for a longer time to maintain acceptable room air temperatures. The swine number is the other important factor for CO_2 simulation: when the swine number was zero, as it was on 31 December in the field study, the room CO_2 concentration was the lowest even though T_o was colder than other days. The presumption that makeup air entering into a farrowing room is independent of concentrations throughout the rest of the building is perhaps a poor assumption as it was in the current work.

3.1.3. Room concentrations of CO and dust—Simulated room concentrations of CO and dust, along with comparative field measure results, are illustrated in Figures 2(c–e) (date given in on-line supplemental Table A4). As shown in Figure 2(c), CO concentration was underestimated in the model, ranging from only 0.25 to 0.31 ppm, while the field measured concentrations ranged from 0.94 to 3.29 ppm. One reason could be the detection limit of the field instrument. The nominal range of the CO sensor was 0–500 ppm with a resolution of 1 ppm. The measured CO concentrations were close to the lower detection limit of the sensor.

The linear regression between measured and simulated inhalable and respirable dust concentration had a modest R^2 (0.34 and 0.40, respectively). In simulated and field measured results, both inhalable and respirable dusts were decreased when the air cleaner was operated. Compared to days when the air cleaner was not in operation and when field measurements were available, inhalable dust concentrations decreased by 32% in simulated results and 31% in field measured results with the air cleaner on. Similarly, respirable dust concentration decreased by 31% in simulated results and 41% in field measured results. Swine number also affected dust concentration since dust generation rate was based on total mass of swine. Maximum values of dust concentration from the model and field measurement occurred on 26 February, when there were large numbers of swine without the air cleaner on.

3.2. Air cleaner operation

Simulations with the condition of “air cleaner off” for the entire winter and “air cleaner on” during the entire winter were conducted and the results are documented in Table 4. The on/off cycle for the field testing data was required to examine the air cleaner performance as part of other research. However a producer will likely run such an air cleaning system for an entire season, permanently ‘on’, or will not have an air cleaning system, which is equivalent to the “off” condition. The air cleaner operation only reduced dust concentrations, by design, because this air cleaner does not remove other contaminant gases (NH_3 and CO_2). When the air cleaner was not operated during the winter season, the inhalable and respirable dust concentrations had three-month mean averages of 0.97 and 0.10 mg m^{-3}, respectively. When the air cleaner was running the entire winter, simulated 3-month mean inhalable and respirable dust concentrations decreased by 35% and 30%, respectively. The room dust concentration decreased linearly with increasing filtration efficiency (Park et al., 2013).

Inhalable dust was removed more than respirable dust because the air cleaner collection efficiency was 95% for inhalable dust and 85% for respirable dust.

Three-month operational costs (electrical and heating) are also given in Table 4. When the air cleaner was turned off during winter, the total operational cost was $1,496. When the air cleaner was turned on, the total operational cost was increased by 58% to $2,359, primarily due to additional power consumption to operate the air cleaner's fan.

4. Limitation and recommendation

One limitation of this study is that the simulation was conducted for only one configuration of a farrowing room. Simulation with Z_{NH3} of 21,000 and makeup air CO_2 concentration of 1,500 ppm showed best results for our barn designed. The Z_{NH3} covers various factors such as ventilation and slurry properties. These values may be different for other swine barns. Differences also exist between this simulated room and high production facility rooms, including room dimensions, crate layout, and pit volume (total and headspace above manure). In addition, other production facilities may house more swine per square foot than this study location and have larger piglet production targets (e.g., 11 piglets per sow), which would yield higher generation rates for multiple contaminants. These differences can affect Z_{NH3} and other parameters in the current model. For buildings with vented heaters or with lower CO_2 contamination in makeup air, results may differ, but the simulation model was set up to account for these differences. Further validation is needed for different barn designs and production densities to evaluate the robustness of the model generated and validated here.

The model could be used to optimize ventilation systems for livestock facilities to provide good air quality at the lowest cost even though the model has limitations. The simulation model provides a useful tool for examining the costs and benefits to installing common ventilation technology to CAFO and, ultimately, making sound management decisions.

5. Conclusion

We improved our original mass and energy balance model to improve room NH_3 and CO_2 concentrations, matching the test conditions in a field study of a swine farrowing barn. An empirical model was used to improve NH_3 simulation, with a substantial but imperfect increase in agreement between simulation and field measurements (R^2 improved from 0.02 to 0.37 with new formulation). To improve CO_2 concentration estimates, higher concentrations in makeup air were required, which was justified by assuming that makeup air into the farrowing room came from other rooms in the building, verified by field data. After optimization for NH_3 and CO_2, air cleaner operation was evaluated. The air cleaner operation only changed dust concentration and does not remove NH_3 nor CO_2. While the operational cost increased by $863 over three months due to air cleaner operation, the concentrations of inhalable and respirable dusts were decreased by 35% and 33%, respectively. The new model was able to simulate a variety of conditions, making it a potential tool for future simulations of IAQ and operational cost in swine farrowing rooms.

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Nomenclature

$\mathbf{A_p}$	surface area of manure, m^2
$\mathbf{A_{pw}}$	overlap area of pit and wall, m^2
$\mathbf{A_{rf}}$	overlap area of room and floor, m^2
$\mathbf{A_{rw}}$	overlap area of room and wall, m^2
$\mathbf{c_p}$	specific heat at constant pressure of air, J kg^{-1} K^{-1}
$\mathbf{ER_{CO}}$	CO emission rate from natural gas combustion, mg m^{-3}
$\mathbf{ER_{CO2}}$	CO_2 emission rate from natural gas combustion, mg m^{-3}
$\mathbf{f}$	un-ionized fraction of the total ammoniacal nitrogen (TAN), dimensionless
$\dot{G}_{COr}$	generation rate of CO by heater, mg s^{-1}
$\dot{G}_{CO2r,heater}$	generation rate of CO_2 by heater, mg s^{-1}
$\dot{G}_{CO2r,swine}$	generation rate of CO_2 by swine, mg s^{-1}
$\dot{G}_{dustr}$	dust generation rate in the room, mg s^{-1}
$\dot{G}_{mean}$	overall mean dust generation rate per 500 kg swine, mg s^{-1}
$\dot{G}_{NH3}$	generation rate of NH_3, mol s^{-1}
$\dot{G}_{NH3,EM}$	generation rate of NH_3 per 500 kg swine, mg s^{-1}
$\dot{G}_{NH3p}$	generation rate of NH_3 in the pit, mg s^{-1}
$\dot{G}_{Pp}$	contaminant generation rate for pit, mg s^{-1}
$\dot{G}_{Pr}$	contaminant generation rate for room, mg s^{-1}
$\dot{G}_{slurry}$	slurry generation rate, m^3 kg^{-1} s^{-1}
$\mathbf{H}$	Henry's constant, dimensionless
$\mathbf{k}$	mass transfer coefficient, m s^{-1}
$\mathbf{m_{piglet}}$	mass of one piglet, kg
$\mathbf{m_{sow}}$	mass of one sow, kg
$\mathbf{m_{swine}}$	total mass of swine, kg
$\mathbf{n_{piglet}}$	piglet number, dimensionless

$\mathbf{n_{sow}}$	sow number, dimensionless
$\mathbf{P_{elect}}$	electricity cost, $ kWh^{-1}
$\mathbf{P_{gas}}$	natural gas cost, $ m^{-3}
$\mathbf{P_m}$	measured concentration of NH_3 or CO_2, ppm
$\mathbf{P_o}$	outdoor concentration of contaminant, ppm or mg m^{-3}
$\mathbf{P_p}$	pit concentration of contaminant, ppm or mg m^{-3}
$\mathbf{P_r}$	room concentration of contaminant, ppm or mg m^{-3}
$\mathbf{P_s}$	simulated concentration of NH_3 or CO_2, ppm
$\mathbf{Q_{ac}}$	total flow rate of air cleaner, m^3 s^{-1}
$\mathbf{Q_{ae}}$	airflow rate of pit-air-exchange, m^3 s^{-1}
$\mathbf{Q_{tp}}$	total airflow rate of two pit fans, m^3 s^{-1}
$\mathbf{Q_{heater}}$	natural gas consumption of one gas heater, m^3 s^{-1}
$\mathbf{\dot{q}_{ac}}$	power consumption of air cleaner, W
$\mathbf{\dot{q}_{gen}}$	total heat generation rate in the room, W
$\mathbf{\dot{q}_{heater}}$	heat generation rate from one gas heater, W
$\mathbf{\dot{q}_{lamp}}$	total heat generation rate from 20 lamps, W
$\mathbf{\dot{q}_{piglet}}$	heat generation rate from one piglet, W
$\mathbf{\dot{q}_{sow}}$	heat generation rate from onw sow, W
$\mathbf{\dot{q}_{swine}}$	total heat generation rate from swine, W
$\mathbf{\dot{q}_{tp}}$	total power consumption of two pit fans, W
$\mathbf{r_{ae}}$	pi-air-exchange ratio, dimensionless
$\mathbf{r_r}$	recirculation ratio, dimensionless
$\mathbf{S_{heater}}$	switch function of heater, dimensionless
$\mathbf{T_f}$	floor temperature, K
$\mathbf{T_{film}}$	manure film temperature, K
$\mathbf{T_g}$	pit wall temperature, K
$\mathbf{T_o}$	outdoor temperature, K
$\mathbf{T_p}$	pit headspace temperature, K
$\mathbf{T_r}$	room temperature, K

TAN	total ammoniacal nitrogen, mol m^{-3}
TC	total operational cost, $
$\mathbf{U_{pw}}$	heat transfer coefficient of pit and ground, W m^{-2} K^{-1}
$\mathbf{U_{rw}}$	heat transfer coefficient between room and wall, W m^{-2} K^{-1}
$\mathbf{U_{rf}}$	heat transfer coefficient of floor and room, W m^{-2} K^{-1}
$\mathbf{V_p}$	pit headspace volume, m^3
$\mathbf{V_{p,max}}$	maximum volume of pit head space, m^3
$\mathbf{V_{p,min}}$	minimum volume of pit head space, m^3
$\mathbf{V_r}$	room volume, m^3
$\mathbf{v_s}$	air speed in the vicinity of the slurry, m s^{-1}
Z	empirically determined constant
$\mathbf{Z_{NH3}}$	coefficient determined by fitting modeled concentration estimates to field measurements, $K^{1.4}$ $m^{0.2}$ $s^{-0.2}$
η_P	removal efficiency of the air cleaner, dimensionless
ρ_a	air density, kg m^{-3}
ρ_{CO2}	density of CO_2, kg m^{-3}

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Appendix

1. Model equations and parameters for temperature and operational cost

Equations (A1) and (A2) describe the energy balances for the room volume and the pit volume (Park et al., 2013).

Room:

$$\rho_a V_r c_a \frac{dT_r}{dt} = \rho_a Q_{ac} c_a T_r + \rho_a Q_{tp} c_a T_p + \rho_a Q_{ae} c_a T_p + \dot{q}_{gen} - \rho_a Q_{ac} c_a T_r - \rho_a Q_{tp} c_a T_r - \rho_a Q_{ae} c_a T_r - U_{rw} A_{rw} (T_r - T_o) - U_{rf} A_{rf} (T_r - T_f) \quad \text{(A1)}$$

Pit:

$$\rho_a V_p c_a \frac{dT_p}{dt} = \rho_a Q_{tp} c_a T_r + \rho_a Q_{ae} c_a T_r - \rho_a Q_{tp} c_a T_p - \rho_a Q_{ae} c_a T_p - U_{pw} A_{pw} (T_p - T_g). \quad \text{(A2)}$$

In our previous model, outdoor temperature (T_o) was simulated using historical seasonal average data for the Cedar Rapids, Iowa, modeled as a combination of two sine waves (Park et al., 2013; Anthony et al., 2014) to account for within and between day temperatures. However, for the current model, T_o was set to the actual temperature of Cedar Rapids, Iowa, U.S. from December 2013 to February 2014, the period of the field study for model validation (CID Airport meteorological data from NOAA's National Climatic Data Center).

The total operational cost was computed using Equation A3, which included continuous operation of heat lamps, the cost of running the heater to maintain temperatures within the optimum production range, and the cost of running contaminant control equipment during each test case using power requirements from device manufacturers (Park et al., 2013):

$$TC = P_{elect} \int_0^{3months} \left(\dot{q}_{lamp} + \dot{q}_{tp} + \dot{q}_{ac}\right) dt + P_{gas} \int_0^{3months} \left(S_{heater} \dot{Q}_{heater}\right) dt \quad \text{(A3)}$$

where P_{elect} is the electricity cost, P_{gas} is the natural gas cost, $\dot{q}_{tp}$ and $\dot{q}_{ac}$ are power consumption of pit fans and air cleaner, respectively. The switch function of heater operation (S_{heater}) was computed by the model as 0 (off) or 1 (on) at any moment in time as determined by the need for the heater to activate to warm the room, based on computed room temperatures. Tables 1 and A1 detail each parameter used in these equations.

Table A1

Input parameters for energy and cost equations.

Parameter	Value	Note
Air density (ρ_a)	1.2041 kg m^{-3}	Assumed dry air at 20.0°C and 101.325 kPa

Parameter	Value	Note
Specific heat at constant pressure of air (C_p)	1,006.1 J kg^{-1} K^{-1}	Assumed dry air at 20.0°C and 101.325 kPa
Outdoor temperature (T_o)	-	Temperature data measured at the Eastern Iowa Airport during Dec 2013 to Feb 2014
Room temperature (T_r)	-	Computed in Equation 2; initial value = 293K
Pit headspace temperature (T_p)	-	Computed in Equation 2; initial value = 293K
Pit wall temperature (T_g) and floor temperature (T_f)	290K (17°C)	Assumed $T_g = T_f$; Field measurement data
Manure film temperature (T_{film})	-	$= (T_g + T_p) / 2$
Heat generation rate from 1 piglet ($\dot{q}_{piglet}$)	24.5 W	$= m_{piglet} \times (4.3 \times m_{piglet}{}^{0.15})$; Brown-Brandl et al. (2004)
Heat generation rate from 1 sow ($\dot{q}_{sow}$)	372.6 W	$= m_{sow} \times (14.11 \times m_{sow}{}^{-0.38})$; Brown-Brandl et al. (2004)
Total heat generation rate from swine ($\dot{q}_{swine}$)	-	$= n_{piglet} \times \dot{q}_{piglet} + n_{sow} \times \dot{q}_{sow}$
Total heat generation rate from 20 lamps ($\dot{q}_{lamp}$)	2,500 W	= 20 × 125 W; Manufacturer
Heat generation rate from 1 gas heater ($\dot{q}_{heater}$)	17,585 W	= 60,000 BTU h^{-1}; Manufacturer; On: Tr ≤ 20.0°C; Off: Tr ≥ 22.2°C
Total heat generation rate in the room ($\dot{q}_{gen}$)	-	$= \dot{q}_{heater} + \dot{q}_{swine} + \dot{q}_{lamp}$
Heat transfer coefficient between room and wall (U_{rw})	0.286 W m^{-2} K^{-1}	Zhang et al., 1993; U-value of ceiling was assumed to be the same as U_{rw}.
Heat transfer coefficient of floor and room (U_{rf})	0.568 W m^{-2} K^{-1}	Zhang and Barber (1993)
Heat transfer coefficient of pit and ground (U_{pw})	0.568 W m^{-2} K^{-1}	Assumed $U_{rf} = U_{pw}$; Zhang and Barber (1993)
Overlap area of room and wall (A_{rw})	238.3 m^2	$= l_r \times w_r + 2 \times (l_r + w_r) \times h_r$
Overlap area of room and floor (A_{rf})	54.6 m^2	$= l_r \times w_r - (4 \times l_p \times w_p)$
Overlap area of pit and wall (A_{pw})	96.6 – 147.3 m^2	$= 4 \times \{(l_p \times w_p) + 2 \times (l_p + w_p) \times h_p\}$
Electricity cost (P_{elect})	0.0807 $ kWh^{-1}	Average industrial price in Iowa during Dec 2013 to Feb 2014
Natural gas cost (P_{gas})	0.27 $ m^{-3}	Average industrial price in Iowa during Dec 2013 to Feb 2014
Natural gas consumption of 1 gas heater ($\dot{Q}_{heater}$)	0.000472 m^3 s^{-1}	Manufacturer
Total power consumption of 2 pit fans ($\dot{q}_{tp}$)	690 W	= 2 × 345 W; Manufacturer
Power consumption of air cleaner ($\dot{q}_{ac}$)	4,950 W	Manufacturer
Switch function of heater (S_{heater})	0, 1	0 = off; 1 = on

2. Feeding function

The overall mean inhalable and respirable dust generation rates per 500-kg swine mass were 567 and 59 mg h^{-1} per 500-kg, respectively (Takai et al., 1998). The mean generation rates of inhalable ($\dot{G}_{dust,i}$) and respirable ($\dot{G}_{dust,r}$) dust were calculated from total swine mass. To account for the fact that dust generation depends on feeding time, dust generation rate was assumed to increase during the feeding as shown in Figure A1. The first feeding was prescribed at 9:00 a.m. and the second feeding at 4:00 p.m.. Dust concentrations at first feeding and second feeding were modeled as four and two times higher than background concentration, respectively, based on previous research (O'Shaughnessy et al., 2010).

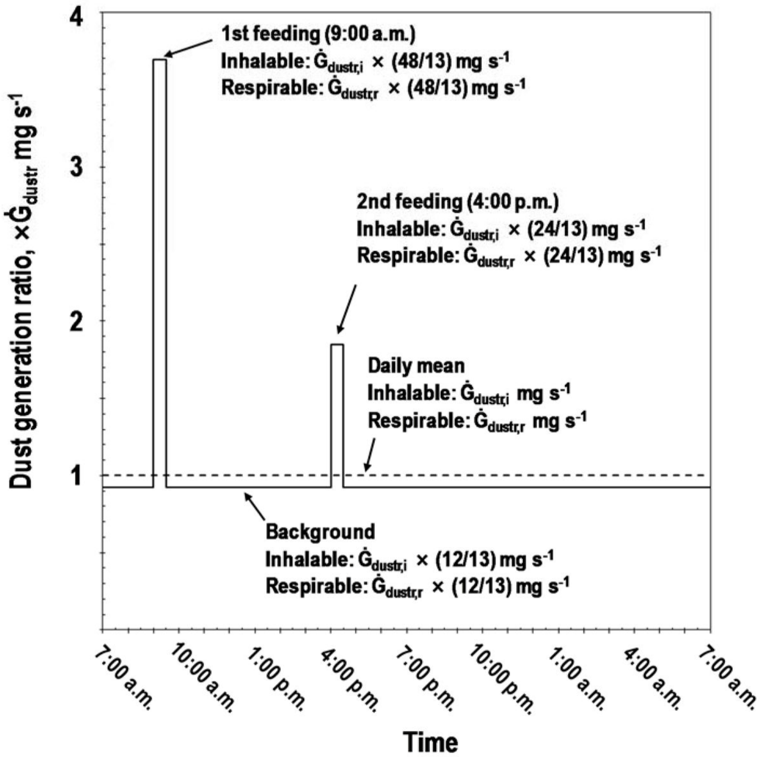

Figure A3.
Time-dependent dust generation rate

3. Input conditions and simulation results

The following tables identify the field conditions at the farrowing barn at the test site that was used to validate the model. These tables detail how the model was adjusted throughout the 90 day simulation period, to represent actual conditions at the test location. Table A2 identifies animals housed in the room (changed over time). Table A3 identifies when the ventilation system was turned on and off (to assess system performance at the test location). Table A4 identifies room-averaged concentrations, measured in the field and modeled, over the testing and simulation periods.

Table A2

Swine number

Date and time	Simulation time, day	Simulation time, s	Sow	Piglet
01 Dec 2013, 8:00 h	0.00	0	0	0
10 Dec 2013, 0:00 h	8.67	748,800	11	0
13 Dec 2013, 8:00 h	12.00	1,036,800	11	64
14 Dec 2013, 8:00 h	13.00	1,123,200	11	63
16 Dec 2013, 8:00 h	15.00	1,296,000	11	64
17 Dec 2013, 8:00 h	16.00	1,382,400	11	64

Date and time	Simulation time, day	Simulation time, s	Sow	Piglet
18 Dec 2013, 8:00 h	17.00	1,468,800	11	68
19 Dec 2013, 8:00 h	18.00	1,555,200	11	69
21 Dec 2013, 8:00 h	20.00	1,728,000	11	77
22 Dec 2013, 8:00 h	21.00	1,814,400	11	79
26 Dec 2013, 8:00 h	25.00	2,160,000	11	74
27 Dec 2013, 8:00 h	26.00	2,246,400	11	74
31 Dec 2013, 8:00 h	30.00	2,592,000	0	0
10 Jan 2014, 8:00 h	40.00	3,456,000	16	0
11 Jan 2014, 8:00 h	41.00	3,542,400	16	0
17 Jan 2014, 8:00 h	47.00	4,060,800	15	11
18 Jan 2014, 8:00 h	48.00	4,147,200	15	8
20 Jan 2014, 8:00 h	50.00	4,320,000	15	18
22 Jan 2014, 8:00 h	52.00	4,492,800	16	30
23 Jan 2014, 8:00 h	53.00	4,579,200	16	57
24 Jan 2014, 8:00 h	54.00	4,665,600	13	54
25 Jan 2014, 8:00 h	55.00	4,752,000	13	76
26 Jan 2014, 8:00 h	56.00	4,838,400	13	75
27 Jan 2014, 8:00 h	57.00	4,924,800	13	85
28 Jan 2014, 8:00 h	58.00	5,011,200	13	91
29 Jan 2014, 8:00 h	59.00	5,097,600	13	99
03 Feb 2014, 8:00 h	64.00	5,529,600	17	120
04 Feb 2014, 8:00 h	65.00	5,616,000	17	119
10 Feb 2014, 8:00 h	71.00	6,134,400	19	82
11 Feb 2014, 8:00 h	72.00	6,220,800	19	86
17 Feb 2014, 8:00 h	78.00	6,739,200	19	117
18 Feb 2014, 8:00 h	79.00	6,825,600	19	117
24 Feb 2014, 8:00 h	85.00	7,344,000	17	96
25 Feb 2014, 8:00 h	86.00	7,430,400	17	95
26 Feb 2014, 8:00 h	87.00	7,516,800	17	102
27 Feb 2014, 8:00 h	88.00	7,603,200	17	100

Table A3

Air cleaner operation

Date and time,	Simulation time, day	Simulation time, s	On: 1 / Off: 0
01 Dec 2013, 8:00 h	0.00	0	0
21 Dec 2013, 9:00 h	20.04	1,731,600	1
22 Dec 2013, 9:00 h	21.04	1,818,000	1
26 Dec 2013, 9:00 h	25.04	2,163,600	1
27 Dec 2013, 9:00 h	26.04	2,250,000	1
31 Dec 2013, 9:00 h	30.04	2,595,600	1
01 Jan 2014, 9:00 h	31.04	2,682,000	1

Date and time,	Simulation time, day	Simulation time, s	On: 1 / Off: 0
11 Jan 2014, 9:00 h	41.04	3,546,000	1
12 Jan 2014, 9:00 h	42.04	3,632,400	1
17 Jan 2014, 9:00 h	47.04	4,064,400	1
18 Jan 2014, 9:00 h	48.04	4,150,800	1
20 Jan 2014, 9:00 h	50.04	4,323,600	1
21 Jan 2014, 9:00 h	51.04	4,410,000	0
28 Jan 2014, 9:00 h	58.04	5,014,800	1
29 Jan 2014, 9:00 h	59.04	5,101,200	1
03 Feb 2014, 9:00 h	64.04	5,533,200	1
04 Feb 2014, 9:00 h	65.04	5,619,600	1
10 Feb 2014, 9:00 h	71.04	6,138,000	1
11 Feb 2014, 9:00 h	72.04	6,224,400	1
17 Feb 2014, 9:00 h	78.04	6,742,800	1
18 Feb 2014, 9:00 h	79.04	6,829,200	1
24 Feb 2014, 9:00 h	85.04	7,347,600	1
25 Feb 2014, 9:00 h	86.04	7,434,000	0

Table A4

Simulation and measurement results for IAQ (Z_{NH3} = 21,000, Makeup air CO_2 concentration = 1500 ppm)

Date	Air cleaner	24-hrmean T_o, °C	Sow/Piglet Count	NH_3, ppm		CO_2, ppm		CO, ppm		Inhalable dust, mg m^{-3}		Respirable dust, mg m^{-3}	
				Model	Field	Model	Field	Model	Field	Model	Field	Model	Field
13 Dec 2013	Off	−5.3	11/64	8.57	5.02 ±1.78	2500	2177 ±92	0.31	1.58 ±1.08	0.94	0.87 ±0.14	0.10	0.20 ±0.03
16 Dec 2013	Off	−7.9	11/63	8.62	5.73 ±1.52	2501	2440 ±101	0.31	2.06 ±0.89	0.94	1.15 ±0.31	0.10	0.22 ±0.05
18 Dec 2013	Off	−0.6	11/68	8.59	6.05 ±1.34	2418	2029 ±130	0.27	1.38 ±0.46	0.94	1.38 ±0.37	0.10	0.17 ±0.04
21 Dec 2013	On	−3.2	11/77	8.73	6.19 ±1.79	2523	2241 ±145	0.31	1.86 ±0.73	0.64	0.96 ±0.37	0.07	0.12 ±0.02
26 Dec 2013	On	−4.8	11/74	8.73	10.53 ±3.59	2498	2251 ±181	0.30	2.89 ±2.51	0.62	1.07 ±0.54	0.07	0.11 ±0.01
31 Dec 2013	On	−13.4	0/0	0.05	0.07 ±0.16	2103	2276 ±100	0.31	3.29 ±2.54	0.00	0.18 ±0.01	0.00	0.10 ±0.01
10 Jan 2014	On	0.1	16/0	10.87	2.50 ±1.24	2410	1990 ±116	0.26	1.73 ±0.99	0.78	0.41 ±0.06	0.08	0.09 ±0.01
17 Jan 2014	On	−11.6	15/11	10.63	9.79 ±4.40	2515	2614 ±79	0.31	2.46 ±1.57	0.74	0.29 ±0.04	0.08	0.10 ±0.01
20 Jan 2014	On	−7.0	15/18	10.65	12.53 ±3.78	2478	2250 ±176	0.29	1.39 ±0.41	0.75	0.50 ±0.31	0.08	0.15 ±0.09
22 Jan 2014	Off	−16.5	16/30	11.73	12.38 ±2.78	2574	2801 ±99	0.31	2.00 ±0.13	1.25	0.78 ±0.15	0.13	0.20 ±0.00
24 Jan 2014	Off	−2.7	13/54	9.77	10.54 ±1.11	2473	2254 ±160	0.28	1.44 ±0.16	1.07	0.60 ±0.07	0.11	0.16 ±0.01
26 Jan 2014	Off	−10.3	13/75	10.24	14.73 ±1.40	2529	2394 ±145	0.29	1.51 ±0.22	1.11	0.82 ±0.11	0.12	0.18 ±0.01
28 Jan 2014	On	−17.1	13/91	10.62	16.48 ±1.23	2600	2907 ±141	0.31	2.11 ±0.32	0.75	0.47 ±0.17	0.08	0.11 ±0.05
03 Feb 2014	On	−10.9	17/120	13.64	16.58 ±3.84	2755	2759 ±158	0.31	1.87 ±0.30	0.96	0.83 ±0.28	0.10	0.13 ±0.01
10 Feb 2014	On	−23.1	19/82	14.83	28.09 ±1.83	2743	3103 ±130	0.31	2.27 ±0.26	1.02	0.92 ±0.15	0.11	0.14 ±0.01
17 Feb 2014	On	−3.1	19/117	14.82	8.73 ±1.30	2675	2505 ±156	0.25	0.94 ±0.46	1.06	1.06 ±0.15	0.11	0.09 ±0.01
24 Feb 2014	On	−11.0	17/96	13.29	10.01 ±2.14	2715	2639 ±91	0.31	1.34 ±0.68	0.94	0.85 ±0.21	0.10	0.13 ±0.01
26 Feb 2014	Off	−13.0	17/102	13.44	7.25 ±1.40	2725	3007 ±136	0.31	1.45 ±0.81	1.45	1.36 ±0.28	0.15	0.25 ±0.01

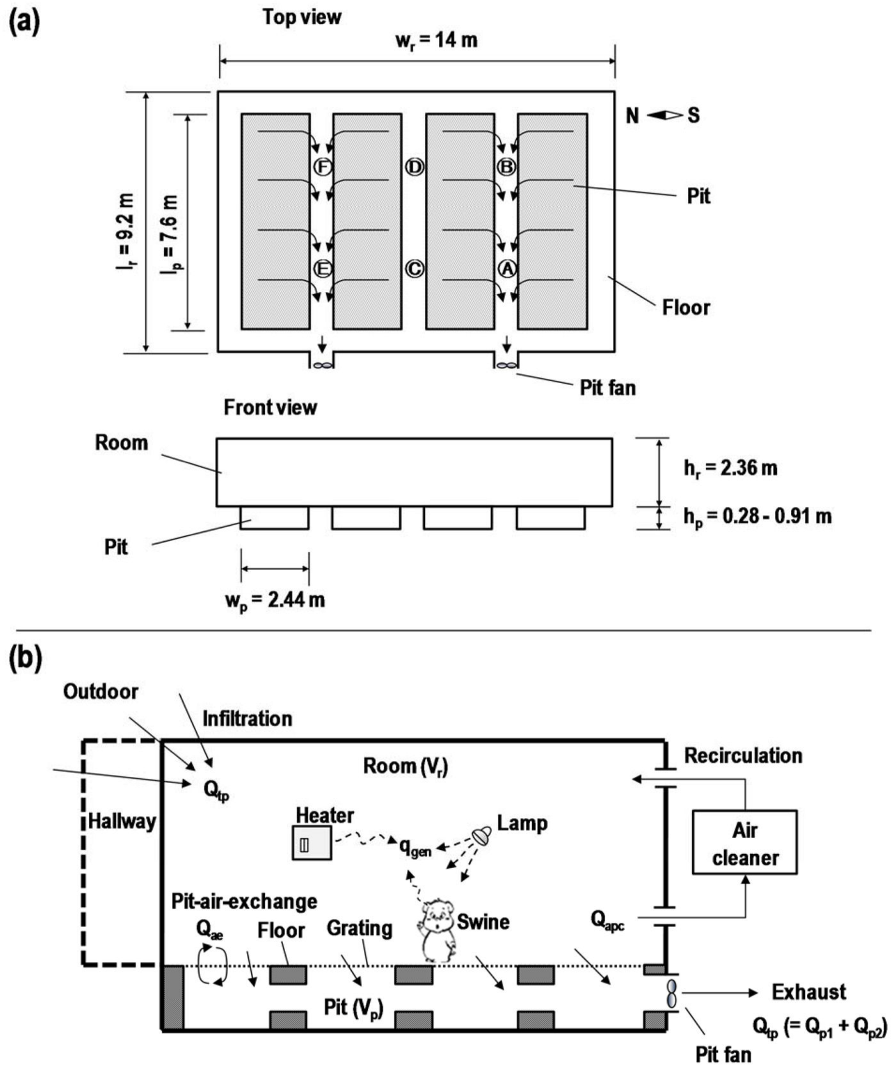

Figure 1.
Schematic diagram of the modeled swine farrowing facility, identifying (a) dimensions and six sampling positions (A – F) for field measurements and (b) airflow pathways.

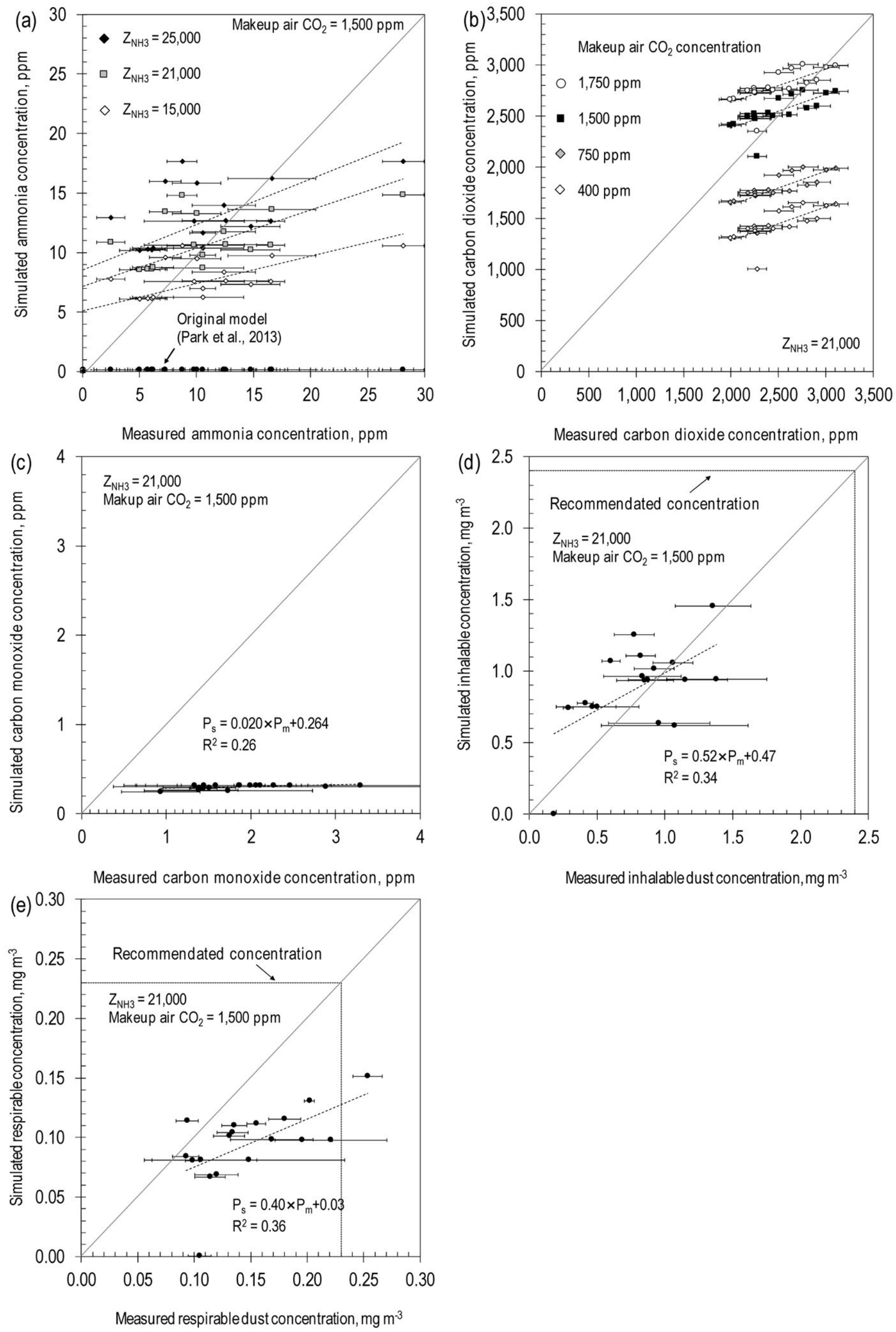

Figure 2.

Linear regression between measured and calculated results for (a) ammonia, (b) carbon dioxide, (c) carbon monoxide, (d) inhalable dust and (e) respirable dust. (*Note* solid line: 1 on 1 line, dash line: trend line, P_s: simulated concentration and P_m: measured concentration)

Table 1

Physical and operational parameters of the test site used as model input.

Parameter	Value	Note
Room volume (V_r)	304 m^3	= 9.2 m × 14 m × 2.36 m
Pit headspace volume (V_p)	Max: 67.5 m^3 Min: 20.8 m^3	= 4 × 2.44 m × 7.6 m × h_P; 0.28 m ≤ h_p ≤ 0.91 m
Total airflow rate of pit fans (Q_{tp})	0.82 $m^3\ s^{-1}$	= 2 × 872 $ft^3\ min^{-1}$
The airflow rate of pit-air-exchange (Q_{ae})	0.08 $m^3\ s^{-1}$	Assumed 10% of the total air flow rate of pit fans Cortus et al. (2010b)
Total flow rate of air cleaner (Q_{ac})	0.47 $m^3\ s^{-1}$	= 1000 $ft^3\ min^{-1}$, per manufacturer
Slurry generation rate ($\dot{G}_{slurry}$),	$8.38\times10^{-10}\ m^3\ kg^{-1}\ s^{-1}$	= 1.16 $ft^3\ AU^{-1}\ day^{-1}$; Chastain et al. (1999)
Piglet number (n_{piglet})	0 – 120	Field measurement (see Supplementary)
Sow number (n_{sow})	0 – 19	Field measurement (see Supplementary)
Mass of 1 piglet (m_{piglet})	4.5 kg	Assumption (10 lb.)
Mass of 1 sow (m_{sow})	196.4 kg	Assumption (433 lb.)
Total mass of swine (m_{swine})	-	= $n_{piglet} \times m_{piglet} + n_{sow} \times m_{sow}$

Table 2

Input parameters for IAQ calculation.

Parameter	Initial room concentration (P_{ini})	Outdoor concentration (P_o)[a]	Generation rate in the room ($\dot{G}_{Pr}$)	Generation rate in the pit ($\dot{G}_{Pp}$)	Removal efficiency of air cleaner (η_P)
NH_3	6.27 ppm	0 ppm	0 mg s^{-1}	Eq. (6)	0
CO_2	1,750 ppm	400 ppm 750 ppm 1,250 ppm 1,500 ppm 1,750 ppm	Heater: Eq. (7) Swine: Eq. (8)	37.5% of CO_2 from swine	0
CO	0 ppm	0 ppm	Heater: Eq. (9)	0 mg s^{-1}	0
Inhalable dust	2.19 mg m^{-3}	0 mg m^{-3}	Eq. (10) Figure A3	0 mg s^{-1}	0.95
Respirable dust	0.23 mg m^{-3}	0 mg m^{-3}	Eq. (10) Figure A3	0 mg s^{-1}	0.85

[a] makeup air for CO_2

Table 3

Linear regression and SSE results for NH_3 and CO_2.

Parameter	Variable		Linear regression $P_s = A \times P_m + B$ P_s: simulated concentration P_m: measured concentration			SSE
			A	**B**	R^2	
NH_3	Z_{NH3}	15,000	0.23	5.12	0.37	602
		20,000	0.31	6.82	0.37	441
		21,000	**0.32**	**7.16**	**0.37**	**438**
		21,500	0.33	7.33	0.37	440
		25,000	0.38	8.56	0.37	524
CO_2	Makeup air CO_2 concentration, ppm	400	0.33	628	0.49	2.0×10^7
		750	0.33	978	0.49	9.6×10^6
		1,250	0.33	1,478	0.49	1.7×10^6
		1,500	**0.33**	**1,728**	**0.49**	$\mathbf{1.1\times10^6}$
		1,750	0.33	1,978	0.49	2.8×10^6

Table 4

Simulation results for air cleaner operation (Z_{NH3} = 21,000, makeup air CO_2 concentration = 1,500 ppm).

IAQ, 3-month average	Air cleaner operation		
	0 on 90 off	59 on 31 off*	90 on 0 off
NH_3	9.00	9.00	9.00
CO_2	2,475	2,475	2,475
CO	0.30	0.30	0.30
Inhalable dust	0.98	0.73	0.63
Respirable dust	0.10	0.08	0.07
Total operational cost, $	1,496	2,062	2,359
Operational cost for air cleaner, $	0	566	863

*Matches field test condition